Staff Paper on the

Review of Ocean Thermal Energy Systems

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Preface

This analysis of the Ocean Thermal Energy Conversion (OTEC) Program was undertaken at the request of the House Committee on Science and Technology. The Committee asked that OTA review the status of OTEC development with particular attention to alternative technical paths for the OTEC concept, current evaluation of economic feasibility, and the most promising markets for OTEC products.

Because of continuing Congressional interest in the subject, OTA prepared two previous analyses of ocean thermal energy systems -- one in 1978 titled "Renewable Ocean Energy Sources: Ocean Thermal Energy Conversion" and one in 1980 titled "Recent Developments in Ocean Thermal Energy." The reader is referred to these studies for more detailed descriptions of OTEC technologies and for analyses of the Federal programs at the time.

OTA sincerely appreciates comments received on a draft of the paper by Eugene Frankel and Daniel Steinway of the House Committee on Science and Technology; by E. J. Francis of the Johns Hopkins Applied Physics Laboratory; by Robert Cohen of Giannotti & Associates; by Thomas H. Daniel, Director of the National Energy Laboratory of Hawaii; and by Norman Sather, Deputy Director of the Argonne National Laboratory.

OTEC Assessment Staff

John Andelin, Assistant Director, OTA
Science, Information, and Natural Resources Division

Robert W. Niblock, Oceans and Environment Program Manager

Project Staff

Peter A. Johnson, Project Director

Dale T. Brown, Analyst

Denzil Pauli, Contractor

Administrative Staff

Kathleen A. Beil Kay Senn Jacquelynne R. Mulder

Economic Analyses Prepared by:

Richard E. Rowberg, Energy and Materials Program Manager

SUMMARY OF FINDINGS

Despite Federal expenditures of over $200 million in the past ten years, the high first cost and uncertainty of economic viability for a large (100 MWe +) OTEC plant continue to deter major commercial investments in this technology.

More near-term possibilities for developing a power-producing OTEC system appear to be in the smaller sizes (1-10 MWe) for shore-based locations on tropical islands where comparative energy costs are very high. There are also opportunities for combining power-production with other end uses such as fresh water production.

Only very small (100 kW) OTEC test plants have been operated to date and only for short periods of time (several months). Much more test data is probably needed even before a small-scale commercial plant is built; however, a few commercial firms have stated they are ready to build an island-based system under the right conditions.

Other than the United States, only Japan has invested substantially in OTEC development, although several other countries have done studies, tests and made proposals for small, island-based OTEC plants.

Under most circumstances, with prevailing fossil fuel costs (both oil and coal), the cost of OTEC-produced electricity appears to be higher than the lower-cost fossil fuel alternatives.

The present DOE program supports almost all of the U.S. OTEC research now underway, and the budget for the program has been substantially reduced in recent years. This analysis indicates that the present program lacks any long-range goals and that the variety of research projects now underway do not constitute a coherent plan. If the program is to make effective use of Federal funds, realistic, achievable goals should be incorporated and the limited funds should be directed at the most important problems.

Past legislation has provided financial incentives for private OTEC investment. Many OTEC proponents believe that these incentives will become important in the future when fossil fuel supplies become scarcer and costs increase again. The Federal OTEC program should also be reviewed in view of how such incentives will affect the long term national energy needs.

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INTRODUCTION

The energy resource to be tapped by OTEC is the temperature difference between surface and subsurface oceanic waters. Numerous concepts have been proposed ranging from shore mounted plants to moored offshore plants to self-propelled ("grazing")[1] plant-ships. Sizes could vary from plants producing a few hundred kilowatts to those generating hundreds of megawatts.[2]

Two basic energy conversion techniques have received the most investigation: the so-called closed and open cycles. While electricity generally has been considered the primary OTEC product, secondary products such as ammonia or methanol have received considerable attention, especially for moored or grazing OTEC plants located in remote areas.

The U.S. Department of Energy (DOE) (and its predecessor, the U.S. Energy Research and Development Administration, ERDA) has funded an OTEC program since FY 1975, expanding the research effort initiated by the National Science Foundation in 1972.

In 1980 Congress passed two laws to encourage the development and commercialization of OTEC technology. The Ocean Thermal Energy Conversion Research, Development, and Demonstration Act of 1980, PL 96-310, established national goals for the demonstration of OTEC systems and directed DOE to pursue OTEC R&D and to establish a pilot plant program. The Ocean Thermal Energy Conversion Act of 1980, PL 96-320, established a licensing and permitting system for commercial OTEC facilities within the National Oceanic and Atmospheric Administration in the Department of Commerce. It also authorized Title XI loan guarantees under the Merchant Marine Act, 1936, for OTEC facilities and plant ships.

By September 1983, over $200 million had been spent on federally funded OTEC development. OTEC expenditures and activity peaked in 1980 and have contracted since then with only the very early phases of a pilot plant program having been accomplished.

Since 1980, there has been a shift in Federal policy towards energy research and development which has affected solar energy research. The current Administration has maintained funding for long term R&D, while reducing R&D financial support for near term technologies. In addition, there has been a reduction in direct Federal involvement in commercialization efforts, while retaining incentives such as tax credits for renewable energy resource development. The Administration's strategy calls for the private

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1 The term "grazing" is used to describe a mode of operation in which the OTEC plantship moves at speeds of about 1/2 knot maintaining its position in ocean regions of maximum temperature differential.

2 Richards, D., Dugger, G.L., and Weiskopf, F.P., Jr., "Ocean Energy Systems," International Symposium-Workshop on Renewable Energy Sources, March 17-22, 1983, Lahore, Pakistan.

sector to be responsible for direct support of commercialization and selected hardware development programs.[3]

DISCUSSION OF THE FEDERAL ROLE

This OTA analysis indicates that with dwindling Federal support of OTEC, much of the major development and demonstration work has ended. Private investments have not filled the void and the remaining efforts are the scaled-down DOE R&D and pilot plant programs. It is, therefore, timely to re-evaluate what has been accomplished to date on OTEC development and what are the most promising future prospects for this unique renewable energy system.

This analysis also indicates that the present DOE program lacks any long range goals. This program consists of two parts: 1) a 40 MWe pilot plant development project, the feasibility design phase of which has just been completed; and 2) a group of small directed research efforts.

The pilot plant project was originally intended to reach a demonstration stage but now the DOE has decided to terminate government funding about one year from now or at the completion of a preliminary design. It is unlikely that either government or industry will thus carry the project to completion and therefore even one more year of DOE funded preliminary design work on this plant does not seem to mesh with any clear long range or short range goals.

The remaining research efforts (R&D) supported by DOE are a mixture of ideas from earlier programs still being completed and newer projects. Research is directed toward a variety of techniques, system design approaches, and end products with too little money for any one to receive the support needed to conduct thorough tests and evaluations. Plans are underway to expand a test facility on Hawaii. It is not clear, however, that the facility can be fully supported by the level of future research planned by DOE, and Hawaii is seeking additional support from industry and foreign investors. Taken together, this work does not seem to be directed toward a clear achievable goal.

Past work has demonstrated that a modest sized (1-10 megawatts electrical output) OTEC plant can be built without extensive new technology development. However, since most commercial applications will need to be either much larger (hundreds of megawatts) or of very specialized application (small islands), past work has not demonstrated commercial economic feasibility. Most OTEC applications do not appear to be competitive at today's prices with more conventional alternatives using fossil fuels. In general, the risks are too high in today's economic climate for private industry to invest in OTEC demonstrations, although one private U.S. company

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3 Congress more than doubled the Administration's $86.7 million budget request for solar programs in FY 84. P.L. 98-50, the Energy and Water Development Appropriations Act, provides $178.6 million for solar, which includes a $5 million general budget reduction. $7 million was appropriated for ocean energy systems (OTEC) to save this program from termination.

has proposed to build and operate an OTEC island plant at competitive rates. (See section on OTEC Development Outside of DOE.)

Most researchers believe that the potential future uses of OTEC fall basically into two categories. The first, near-term potential market for OTEC technology would be to provide electrical power for those populated areas of the world located near the OTEC thermal resource - tropical islands and coastal nations. These markets generally would be able to utilize shore-based OTEC plants on the scale of 100 kWe to 100 MWe. Though such plants are of higher risk and require larger capital investment than conventional power sources, they may promise reduced energy dependence for nations now totally dependent on imported hydrocarbon fuels. Though some applications in Hawaii, Puerto Rico, the Virgin Islands, and the Pacific Trust Territories may exist, this near-term small-scale plant development is not significant compared to total domestic U.S. energy needs. Assuming eventual OTEC commercialization, its importance to the U.S. could be two-fold: first, it offers a possible foreign market for U.S. industry; second, participation in the development of small-scale OTEC plants for tropical markets may provide U.S. industry with the opportunity to gain expertise and background to participate in any future development of large-scale OTEC's.

A second category of potential OTEC development, large-scale floating plants, probably using the electricity produced for in situ processing of energy-intensive end products, is a more uncertain, long-range application. A glance at the world map indicates the necessity of floating plants for any significant utilization of the OTEC thermal resource. The technical difficulties and inherent inefficiencies involved in transmitting electricity from a distant ocean-based plant to population centers on shore make in situ utilization of the energy relatively attractive. Large floating plants -- producing products such as hydrogen, ammonia, fertilizer, methanol, aluminum, or scarce metals from manganese nodules -- may have potential to free mainland energy resources for other domestic uses. While there is a great deal of uncertainty about when and if such large scale floating plants would be operated, if it occurs, it is possible that their development would be based on expertise developed in the smaller, island applications. An assessment of the national interest in U.S. participation in this progression could be included in the formulation of goals for the U.S. Federal OTEC program.

Two options appear worth considering for present planning of Federal OTEC efforts. One would be to continue government support of various research and engineering development projects to continually improve the base of knowledge and reduce uncertainties so that the private sector may be better able to finance a future venture but to better plan and coordinate these small projects so that they serve a common goal. The second is to select a small, specialized application, such as a small island-based test plant, where test and evaluation work may help show both economic and technical feasibility for certain systems or products. Both approaches have many variations but it is clear that if long range goals were better defined, a plan to meet those goals could be optimized. Lacking such goals, the Federal effort has no focus.

The following sections describe 1) OTEC systems and concepts, 2) the DOE OTEC program, 3) OTEC development outside of DOE, 4) a review of ongoing OTEC R&D subjects, and 5) a review of OTEC markets and economics.

OTEC SYSTEMS AND CONCEPTS

The basic concept[4] of ocean thermal energy conversion is to extract energy from the temperature difference between surface and subsurface oceanic waters. Solar energy has been absorbed and stored as heat in the upper layer of the ocean; cooler water from polar regions lies below. The cost of energy recovery drops as the temperature differential increases. The temperature difference between the surface layer and water 1000 meters deep is at least 20°C in equatorial areas year around. Further north or south, the maximum temperature difference is less and it varies over the year. Thus, OTEC is best suited to equatorial regions. Because of the relatively small temperature difference, enormous volumes of warm and cold water must pass through the facility to generate a given power as compared to cooling water requirements of a typical fossil fueled generating plant. However, the availability of huge quantities of ocean thermal resources allows the possibility of very large OTEC baseload plants. OTEC plant concepts range from shore mounted plants with ocean intake pipes to fixed and moored offshore plants to drifting plantships. Ideal OTEC resources are in the tropical and subtropical regions. Applications which have been proposed to supply electricity to the continental United States are unlikely to be economically feasible within the next several decades.

OTEC techniques are based on either the so-called closed or open cycles. The DOE has thus far concentrated its research and development efforts on the closed cycle system. In the closed cycle plant, warm surface water is used to evaporate an auxiliary working fluid such as ammonia or Freon. The vaporized working fluid drives a turbine which in turn drives an electrical generator. Cold water from a depth of possibly 1000 meters is used to condense the vapor after it has passed through the turbine, much like in a steam power plant. The working fluid returns to the evaporator to be recycled. The Mini-OTEC demonstration plant, operated in 1979 in Hawaii by the State and Lockheed, is an example of this system.

The open cycle system, experimentally demonstrated by Claude in Cuba in 1930, uses the warm sea water as the working fluid. The pressure above the warm water is lowered sufficiently for the water to boil and vaporize. This vapor is used to drive the turbine. Cold, deep water is required to condense the water vapor exiting from the turbine.

The cold water intakes will be similar for either the closed or open cycle systems. If a shore-based or fixed, near-shore concept is used, large pipes running along the ocean floor are installed to carry cold water from a depth of approximately 1000 meters to the on-shore and fixed near-shore plants. Vertically suspended pipes would be used to carry cold water up to moored or drifting plants. Turbines would be used to generate electricity as the primary energy product. For on-shore and shallow water near-shore, fixed plants, cable transmission of the electricity from the plant does not represent a technological problem. However, for offshore plants moored in deep water, sufficient technology has not been demonstrated or developed for

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4 There are many overviews of the OTEC process. A recent summary is given in Richards, Dugger, and Weiskopf, 1983.

the high powered riser cables which would extend vertically from the plant to a sea floor cable to transmit electricity ashore. Production of energy-intensive secondary products, such as ammonia or methanol, also has been proposed for moored or drifting OTEC plants which could be sited far at sea in tropical waters.

In addition to the problems associated with large OTEC plants there are also environmental concerns. The large volume of cold deep water used in the condensers will create an effluent that is colder and richer in dissolved inorganic nutrients than the local surface waters. The effluent from the warm water side of the plant may contain chlorine for prevention of micro biofouling. The assessment of potential environmental problems may require the operation of small plants over extended periods to gain sufficient data.

In the past few years the concept of aiding undeveloped island countries (and U.S. territories) by providing OTEC power plants has been proposed. Countries engaged in such OTEC activities include the U.S., France, Japan, the Netherlands, Sweden, Jamaica, Indonesia, the Society Islands (Tahiti) and the island Republic of Nauru. Several projects have been initiated with cost-sharing among the government of an industrial country and its industry and the government of a recipient island. Only in the cases of Japan/Nauru and Japan/Tokunoshima have actual systems (a 100 kWe gross, 35 kWe net plant and a 50 kWe plant)* been installed and operated. At these sites, the OTEC plants were used not only to demonstrate the system but also to collect experimental operational data.

The DOE OTEC program of the seventies stressed systems and cost studies for moored and grazing commercial OTEC plants of the 100-400 MWe size. These studies ultimately indicated some major technological problems that would require engineering development and testing of:

- power transmission cables to shore,
- heat exchangers,
- sensitivity of heat exchangers to biofouling, and
- cold water pipes.

A number of engineering design studies and laboratory or small scale tests were conducted. However, the only "large scale" test done was a 1 MWe heat exchanger test program using a converted tanker (OTEC-1). This was initiated in 1979 and cancelled about 2 years later with only a few months of actual at-sea tests accomplished rather than several years of tests which most researchers thought to be needed.

Following the major systems and cost studies of the 1970's, the DOE program of the 1980's has focused on three aspects: 1) the concept

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* To be accurate, plant sizes should be described in terms of either the gross or net electrical power output. The net power output equals the gross power less electrical auxiliaries such as electric powered pumps that are needed to run the plant. In actual practice, however, many plant sizes are given in the literature without such notations and therefore may substantially overstate their capabilities.

formulation and preliminary design of a 40 MWe pilot plant, 2) the continuation of applied research directed to solving problems highlighted in the prior years, and 3) research into alternative OTEC concepts (i.e., moored and grazing OTEC powered chemical plantships and open cycle OTEC concepts).

The avowed objective of today's overall DOE program has been to support research in order to lower risks to industry and the public in the development of alternative energy resources. In the case of OTEC, the objective has been to provide basic data to lower the major technological risks to encourage industry to undertake development of commercially competitive OTEC plants. Such an objective is good but much too vague upon which to base a well-defined and effectively managed program since there is no way to judge when this objective has been reached.

THE DEPARTMENT OF ENERGY OTEC PROGRAM (as of September 1983)

The Department of Energy's program in OTEC R&D has been redirected from emphasis on very large offshore plants and supporting technology to smaller onshore closed cycle plants and related technology. Limited research is continuing in new concepts and components for open cycle plants. The program in 1983 has two major components: 1) completion of the preliminary design of a 40 MWe pilot plant; and 2) R&D on a variety of concepts, systems and components. DOE funding for the pilot plant effort is scheduled to be closed down in 1985 upon the completion of the recently awarded cost-sharing 18 month contract for the preliminary design of a 40 MWe shore-sited closed cycle plant.

The remaining part of the DOE program, general R&D, is described in the 1983 program outline by DOE (see appendix A). This program was formulated to a considerable extent from the results of a meeting of OTEC investigators called upon to identify critical OTEC technologies.

The OTEC component research program is directed toward tests of components for both closed and open cycle plants, as well as further investigation of biofouling, corrosion, and erosion problems. Work on open cycle concepts includes development and tests of evaporators, deaerators, and condensers. The ocean technology R&D efforts are moving away from technology for offshore OTEC plants, (i.e., problems related to suspended cold water pipes), to technology for near shore plants, (i.e., bottom-mounted cold water pipes). Studies of alternative, secondary products of OTEC, (i.e., methanol), are being supported at a low level. Studies of alternative geothermal heat sources for shore mounted plants are also continuing at a low level, as are studies related to the environmental impacts of OTEC.

1. The DOE Pilot Plant Program

The original objective of the Pilot Plant Program was to demonstrate the economic and technical feasibility of an ocean thermal energy conversion plant approaching a commercially viable size. A 1/10th scale, 40 MWe net output plant was selected. In September 1980 DOE issued a Program Opportunity Notice (PON) for a six phase program. Contractors were expected to share 15 to 40 percent of the costs for Phases I-VI inclusive. DOE has subsequently

decided to terminate government funding for the progam at the end of Phase II.[5] The initially planned phases were:

Phase I - Conceptual design
Commenced February 1982, completed June 1983

Phase II - Preliminary design
18 months commencing September 1983

Phase III - Detail design

Phase IV - Construction, deployment, and acceptance testing

Phase V - Joint operational testing

Phase VI - Transfer of ownership and contractor operation

Out of eight proposals for the concept design phase, two contractors were selected: General Electric (GE) and the Ocean Thermal Corporation (OTC). Both proposed near-shore OTEC plants to be sited off Kahe Point, Hawaii, with electricity to be transmitted by cable to a nearby oil fired plant of the Hawaiian Electric Company. Phase I contracts each cost $900,000 to the Government with each contractor sharing about 30 percent of this cost.

The General Electric approach was to place the plant on a fixed steel platform 1.6 km offshore in a water depth of 100 m. The heat exchangers and associated piping were to be mounted on the platform below the water-line and thus exposed to the ocean environment. The heat exchangers were to be of a compact, flat plate, aluminum design. The working fluid was to be Freon. The Cold Water Pipe (CWP) was to run along the ocean floor from the platform to the depth of the deep water intake.

The Ocean Thermal Corporation approach was to place the plant, including the heat exchangers, associated piping and turbine in a concrete, land-based containment structure. This structure was to be located on an artificial island built 180 m offshore in approximately 9 m of water and connected to the shore by a causeway built of rubble material. The heat exchangers were to be horizontal shell-and-tube design fabricated of titanium. The OTC also proposed to use heated effluent from the Hawaiian Electric Company power plant to enhance the temperature of the near-shore, surface intake water.

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5 Program Management Plan, FY 1983 Annual Revision, Ocean Thermal Energy Conversion, Ocean Energy Technology Division, Office of Solar Electric Technologies, U.S. Department of Energy (undated).

Results of Phase I: Conceptual Design

Both of the proposal concepts were modified during the concept design phase.[6] Some of the findings of this phase were common to both contractor efforts.

GE discovered that their conceptual fixed structure had to be modified considerably in order to resist large overturning forces resulting from the impact of waves on the submerged heat exchangers. Costs and questions as to the long-term performance of the enhanced heat exchangers shifted the selection of the working fluid from R22 Freon to ammonia.

The OTC concept development study indicated that plant costs could be decreased by moving the plant to 550 m offshore in 15 m of water. The artificial island concept was abandoned in favor of increasing the fabricated depth of the land-based containment structure so that it could sit directly on the sea floor. Rubble would be used to prevent scour. However, the rubble causeway to shore concept was replaced by a concrete trestle.

Rather than extending the cold water pipe to the 1000 m depth required to obtain 5 C water, both General Electric and OTC found that, for the same power output, overall system cost savings could be achieved by reducing the CWP pipe diameter and length. The CWP savings more than offset the additional costs associated with the increased pumping and larger heat exchanger areas required to provide the same 40 MWe output from a smaller temperature differential. Because of the greater lengths and bottom mounting involved, optimizing the CWP costs is much more critical for shore or shelf plants which use ocean floor mounted pipes than for floating plants which use vertically suspended pipes.

For either the GE or OTC plant sites, the extreme variability of Hawaiian waves and currents makes existing ocean wave data and current measurements inadequate as a basis for estimating expected extreme loads and forces. Such estimations would be necessary for structural design of the Cold Water Pipe.

The Phase I contracts were completed in mid-1983, and the Department of Energy, after review of that work and the evaluation of Phase II proposals from GE and OTC, decided to fund only one contract (with OTC) for Phase II. DOE is now in the process of negotiating for the second phase with the Ocean Thermal Corporation consortium. Phase II has been estimated to take 18 months

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6 Castellano, C. C., Midboe, E. A., and Hagerman, G. K. Jr., "The U.S. Department of Energy's 40 MWe Ocean Thermal Energy Conversion Pilot Plant Program: A Status Report," Joint MTS/IEEE Oceans 83 Conference, August 1983, San Francisco, CA.

to complete at a cost of $5 million to the federal government and a cost sharing of about $2.1 million by the OTC consortium.[7]

Since DOE stated in the July, 1983, Ocean Energy Technology Assessment planning document that it is not going to fund additional work in the OTEC pilot plant project beyond Phase II, it is important to consider what the government and industry are going to gain from the Phase II work. Possible answers may include:

- o Identification of difficult engineering areas requiring additional research;
- o Reduction of industry's perceived risks in pursuing the development of the OTEC concept; and
- o The development of more credible cost analyses of OTEC.

At present, DOE has not stated specific objectives for the results of the Phase II work consistent with the stated cutoff of Federal funding for the program at the end of Phase II.

2. OTEC Testing Facilities

The commercial financing and construction of large, capital intensive commercial plants having outputs of 100 MWe and greater will require the reduction of risks to some level undefined at present. In order to develop and validate the state of technology and estimate risk levels, critical OTEC components must not only be demonstrated but also operated for some considerable periods of time in the ocean water environment. Some tests can be conducted in a land-based shore facility where, for example, many heat exchanger arrangements can be thermally tested. However, if the system is to be used at sea, the design and tests must take into account plant motions. While short term tests may yield much data, long-term cumulative tests are also needed.

Two notable at-sea OTEC experiments have been conducted. One of modest size and cost, Mini-OTEC,[8] was conducted and funded by private industry (Lockheed and associated companies) and the State of Hawaii. Mini-OTEC was a closed-cycle plant mounted on a Navy barge and moored about 2.2 km off Keahole Point, Hawaii, in August 1979. The plant was operated for short periods (up to 10 days) over 4 months. The Mini-OTEC demonstration was the first OTEC plant ever to produce net electrical power output (50 kWe gross, 15 kWe net). The 1980 OTA report on OTEC discusses Mini-OTEC in more detail.

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7 The OTC Consortium consists of the Ocean Thermal Corporation, TRW, Hawaiian Electric Co., R. J. Brown Ltd., Burns and Roe, Inc., Ed Miller Associates, and Offshore Technology Corp.

8 Owens, W. L. and Trimble, L. C., "Mini-OTEC Operational Results," Journal of Solar Energy Engineering, August 1981, vol. 103, pp. 233-235.

The second at-sea test, OTEC-1, was a DOE-funded heat exchanger test program.[9] This 1 Megawatt heat exchanger test facility was installed on a converted surplus tanker in 1980. Auxiliary equipment, such as a cold water pipe, pumps and test instrumentation, were included but no power system was built because the plant was intended only for testing various heat exchanger designs. OTEC-1 also was moored off Hawaii. One conventional type of heat exchanger was fitted and tests were run for short periods over about 4 months during 1981. OTEC-1 was costly (total costs were about $60 million or almost 30% of the entire 9 year's DOE OTEC budget) but produced limited results. This experiment became operational just as the entire DOE solar program was being reduced and redirected, and funding for the operation of OTEC-1 was eliminated.

The OTEC program has gone through several phases of testing. Because of the potential for micro-biofouling of heat exchangers, field studies of biofouling have been conducted at several potential sites. These tests have been followed by more thorough sea water laboratory studies and biofouling cleaning and prevention tests at the Hawaiian Seacoast Test Facility (STF) located at the Natural Energy Laboratory of Hawaii (NELH).[10] Tests have indicated that small amounts of chlorine will eliminate micro biofouling (slimes), the type of fouling that occurs in the heat exchangers.

Initial tests of heat exchanger components were run at inland stateside laboratories using fresh water--the normal power plant coolant. The next step was testing at sea in Puerto Rico, followed by the OTEC-1 tests. The shipboard biofouling tests were limited. Further tests will be required at the STF using various levels of micro-fouling prevention measures. The shipboard tests were costly and DOE had been advised several years prior to these tests to develop an appropriate on-shore testing facility.[11]

Sea tests generally are very expensive, and unless very sophisticated measuring and recording equipment is used, quantitative data may not be obtained. Thus, the use of at-sea facilities generally should be reserved for later testing. However, specific and carefully planned early at-sea tests may be important to uncover operational problems. Factors other than cost and potential lack of quantitative data can preclude the efficient use of at sea testing: at-sea tests often become inflexible due to logistics, scheduling, crew size, and lack of space.

If the DOE OTEC program is to continue it will need to run quantitative laboratory and at-sea field tests. Due to the costs involved, industry is unlikely to undertake such tests in the absence of an assured commercial

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9 Richards, William E., "Ocean Energy Technology Program," Oceans '83, MTS/IEEE Conference, Aug. 29-Sept. 1, 1983, San Francisco, CA.

10 Natural Energy Laboratory of Hawaii, "1982 Annual Report," The Natural Energy Laboratory of Hawaii, Keahole Point, Hawaii.

11 Panel on Ocean Thermal Energy Conversion, Selected Issues of the Ocean Thermal Energy Program, Marine Board, National Research Council, 1977, Washington, D.C.

market. Biofouling, corrosion, and erosion research, which will involve long-term data gathering, are several testing aspects. These tests involve material studies as well as specific equipment designs. The efficiency and performance of evaporators, condensers, other types of heat exchangers, demisters, evacuators, special OTEC pumps, and coupled interacting components are among the many needs of OTEC. Importantly, comparable data must be obtained in many cases in order to properly evaluate components. Likewise, the loading must be controllable and measureable. Tests may be desired at different potential OTEC sites to gain site variable data. However, facilities for testing are generally costly to set up and maintain, and more than one general purpose testing facility would be difficult to justify if flexibility and sufficient test instrumentation are to be provided at each.

The DOE OTEC program recently has been supporting the development of the Seacoast Test Facility at NELH for component testing.[12] It is understood that planning for improvement and expansion of this facility is underway. What is not clear, however, are the goals of the DOE OTEC research and development program. Without these, any justification of the facility becomes vulnerable.

OTEC DEVELOPMENT OUTSIDE OF DOE

Most major programs in the development of OTEC systems have thus far been sponsored by the U.S. Department Of Energy. In 1979, Mini-OTEC was sponsored by private industry and the State of Hawaii. Of a number of foreign projects, only Japan's efforts appear to be at an annual funding level which approaches that of the U.S. With the exception of some state support of the Seacoast Test Facility at NELH and of the 40MW pilot plant design, there is very little non-federal support for OTEC work at present.

There is no current support of OTEC development by U.S. electric utilities beyond the cost-sharing on Phase II of the DOE Pilot Plant program. It is generally agreed by most U.S. utilities that, unless there is a very large increase in the cost of petroleum and other fossil fuels, OTEC plants will not become competitive. Further, in the absence of pilot plant data, considerable technical risk is associated with the development of large OTEC plants capable of feeding the power grid. OTA has not been able to identify any major privately-supported ongoing development of OTEC technology. This is in contrast to considerable private interest and some direct private funding of OTEC development just three years ago. The cost-sharing support of the Pilot Program by the OTC industrial consortium is important, but does not assure continued OTEC development independent of government support.

Recently a private company, the Ocean Thermal Energy Corporation of Oak Park, Ill., has made a proposal to the Government of Jamaica to build and operate a land-based OTEC plant of about 12 MWe size and to sell electricity to the islands's utility corporation at just over 8¢/kWh. We have not obtained technical or economic feasibility data concerning this proposal and

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12 Hillis, David L., Stevens, Herbert C., and Panchal, Chandrakant B., "An Enhanced Test Facility for OTEC at Keahole Point," Oceans '83, Aug. 29-Sept. 1, 1983, San Francisco, CA.

it appears that the company has not previously participated in any of the DOE OTEC development work. The company claims to have a number of patents on technologies of OTEC components that will markedly improve the commercial feasibility of OTEC plants for Caribbean islands, especially where water is also a marketable product.[13]

Some research companies have been active in developing new concepts. For example, R&D Associates, a relatively small company, originated their patented mist-lift concept before receiving DOE support. In OTEC related work, R&D Associates are now primarily supported by DOE. CREARE, INC., another company presently involved in open cycle OTEC research, is primarily funded for its OTEC efforts by DOE. SETS, Inc., a Hawaiian based consulting firm, has completed a detailed design of a 1-acre solar pond/OTEC system, funded by the State of Hawaii.

1. Foreign OTEC Development

While the French were the first to construct an energy conversion system for extracting stored solar energy from the sea, numerous countries are now engaged in some level of OTEC research. Many of these countries are considering OTEC either as a future alternative energy resource or as a special application to particular energy problems. The programs of countries, other than the United States, that are engaged in OTEC research and plant development are summarized below:

Japan/Republic of Nauru

In 1980 the Ocean Development Council and the Industrial Science and Technology Council of Japan adopted OTEC as an alternative energy development target.[14] OTEC was upgraded from fundamental research to the level of system development, and a project was authorized to develop a 1 MW ocean-based OTEC experimental plant. Considerable OTEC efforts are now underway in Japan. The Mitsubishi Company, the Toshiba Corporation of Tokyo, the Tokyo Electric Power Company, and Nagasaki and Saga University are all involved. Funding by the Japanese government in 1983 is about 6 million dollars.

The Tokyo Electric Power Company and Toshiba built and operated a 100 kWe gross (about 35 kWe net) test OTEC plant installed at the Republic of Nauru, an equatorial island country in the Central Pacific. The Nauru installation is a closed cycle plant using Freon as the working fluid and was used as an experimental facility to obtain performance data for various temperature differentials. Details of Nauru's participation in the project are not

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13 Telephone conversations with Dr. Raymond Wright, Petroleum Corporation of Jamaica, and with Mr. Robert Morgan of Ocean Thermal Energy Corporation, October 1983.

14 Kamogawa, Hiroshi, "OTEC Research in Japan," Energy V5, pp. 481-492, 1980, Pergamon Press; and Kamogawa, Hiroshi, "A Short Overview of Japanese Ocean Applications," Conference Proceedings, Seventh Ocean Energy Conference, Department of Energy, Washington, D.C., June 1980.

available. Fifty percent of the cost was subsidized by the Japanese Ministry of International Trade and Industry.

The Kyushu Power Group 50 kW plant at Tokunoshima, Japan was completed with the laying of the cold water pipe in June 1982. Power output commenced in September 1982 and is expected to continue with operating experiments over a two year period. This plant is also 50% subsidized.

Mitsubishi Heavy Industries has also built a 100 kWe test facility to be operated on Okinawa. They also are in the process of designing 1 and 3 MWe plants.[15]

In general, the Japanese program is directed toward developing the broad range of technologies required for OTEC and building small plants for both end use and experimental purposes. These small plant design, construction, and test efforts are being followed by the development of larger systems.

France and their Island Territories

One million people live in French communities on tropical, fuel dependent islands. The French OTEC program is directed toward meeting the needs of these islands and ultimately for international commercial purposes.[16,17] The program is managed by the Centre National pour l'Exploitation des Oceans (CNEXO). The French have completed a feasibility study focused on the development of small plants in the 1-15 MWe range using both open and closed cycles and both onshore and offshore siting. A component testing program began in the summer of 1980 and was expected to continue 3 years. Future construction of an OTEC pilot plant in Tahiti was planned for the mid 1980's.

The first phase feasibility studies were funded 2/3 by the government and 1/3 by private funds. The results of the feasibility study indicated that a floating open cycle 7 MWe OTEC plant and a 10 MWe closed cycle shore plant are competitive with diesel electric power in Tahiti. Offshore plants of these sizes are more competitive because of the lower pipe costs for vertically suspended cold water pipes. The study indicated that there was a market for OTEC plants that could also produce fresh water for isolated tropical islands.

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15 Personal communication between Dr. Kenji Okamura and D. C. Pauli, August 1983.

16 Marchand, Phillipe, "Recent French OTEC Work in the Area of OTEC Systems," Conference Proceedings, Seventh Ocean Energy Conference, Department of Energy, Washington, D.C., June 1980.

17 Marchand, Phillipe, "The French Ocean Energy Program," Conference Proceedings, Seventh Ocean Energy Conference, Department of Energy, Washington, D.C., June 1980.

The French, sponsored by CNEXO, are now investigating the feasibility of a 5 MWe OTEC plant for Tahiti.[18] Temperature and topographic surveys around the island have been conducted. Both open and closed cycle systems are being investigated.

Indonesia

The Netherlands, in cooperation with the Indonesian Government, have surveyed areas at Bali and other islands for favorable locations to site an OTEC plant. They have completed a feasibility study and preliminary design for a 100 kWe system at a site on the north shore of Bali and have started a detailed design. Both Dutch and Indonesian companies are involved in the project. Construction of the 100 kWe plant is scheduled to begin in 1984.

Jamaica

OTEC investigations have been underway in Jamaica for the past 4 years by the Petroleum Corp. of Jamaica. Swedish and Norwegian governments and private industry provided both financial and technical assistance for the work which has included site surveys; a preliminary design of a 1 MWe, shore-based closed cycle-plant; and a series of biofouling tests at the selected site on the south shore of Jamaica near Kingston.

The Jamaicans have estimated that construction of the 1 MWe plant would cost $16 million and they have sought various combinations of both government and commercial grant and loan financing. At present, this project is inactive because no financing has been identified.

The U.S. Department of Energy's Argonne Lab recently sent a technical advisor to Jamaica to discuss OTEC work in general and to help evaluate the potential of a combination Solar Pond/OTEC system for the island.[19] Argonne has issued a short paper indicating that such a system could be feasible and offers some technical advantages (a smaller and shorter cold water pipe needed) but also environmental disadvantages (large land requirements).

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18 Marchand, Phillipe, "The French OTEC Program," Joint MTS/IEEE Oceans'83 Conference, San Francisco, CA, August 1983.

19 Sather, Norman F., "Report of Foreign Travel to Jamaica," Argonne National Laboratory, Sept. 8, 1982, Argonne, IL.

REVIEW OF OTEC R&D SUBJECTS

The following discussion of OTEC R&D by category is intended to provide a review of work to date, the status of technological achievements and any problems or opportunities which have been identified. The discussion has been broadly divided into 1) component and subsystem R&D, and 2) alternative systems and applications.

1. Component R&D

There are numerous component, material, and environmental considerations that have to be addressed in order to design and construct a closed cycle OTEC plant that will have the long life necessary to amortize the contruction costs.[20,21] The major components undergoing development are: heat exchangers, power transmission cables, and cold water pipes.

Heat Exchangers

The overall OTEC efficiencies are so low that gains in the efficiency of each of its components become important. In closed cycle systems the important components are the evaporators, turbines, and condensers. The component efficiencies of the condensers and the evaporators relate to their design, material, and fouling prevention techniques.

Three materials have been in the forefront for evaporator and condenser use: aluminum, titanium and stainless steel. Heat transfer properties, enhancement capability, biofouling cleaning/prevention, corrosion resistance, produceability, and cost are the key selection criteria.

Studies of enhancement techniques for heat exchangers using these materials, particularly aluminum, are subject to continuing R&D. The Seacoast Test Facility at Keahole Point, Hawaii, is being used for enhancement tests as it has been for biofouling studies. Various techniques can improve the heat transfer capability by significant factors. In conventional power plant heat exchangers, where the temperature differentials are much greater, heat transfer coefficients are not so critical. In OTEC heat exchangers, small amounts of biofouling can dramatically affect the heat transfer. In preliminary biofouling cleaning/prevention studies, the use of low levels of chlorine, applied one hour per day for prevention of the buildup of biological slimes (microfouling), has been shown to be very effective. With chlorine, no change in heat transfer has occurred after nearly 2 1/2 years of continuous warm water flow through small heat exchanger test units. No biofouling at all has occurred, in the absence of prevention techniques, in 15 months of cold water flow. However, only short duration tests on large heat exchangers have been conducted to date, and commercial OTEC plants will have to sustain high reliability and performance over long time periods (decades). Corrosion tests also have been performed and indicate that aluminum alloys would survive 30

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20 Richards, "Ocean Energy Technology Program," 1983.

21 Meridian Corporation, "Ocean Energy Technology Assessment," Meridian Corporation, July 1983, Falls Church, VA.

years in a warm water evaporator, but might fail more quickly in a cold water condenser.

Power Transmission Cables

Power cable technology applicable to the transmission of electrical power from large moored, offshore OTEC plants to shore is not sufficiently developed or tested to assure the long life required of such cables. The riser section of the cable running from the ocean floor to the OTEC power plant is of particular concern.[22]

Factors which make the development of OTEC electrical transmission cables difficult are: 1) the weight of the internal conductor and associated insulators and sheaths, 2) the long vertical length of the cable and the associated deep water ambient pressures, and 3) the motion of the platform responding to sea conditions. The internal elements of the cable have to be coupled tightly to the outer armor to prevent relative motion (sleeving). The materials used must also be highly resistant to failure caused by bending, corrosion, pressure, and long-term loading forces that would be imposed on them in the OTEC, thirty year design life application.

Two types of cables have been investigated by the OTEC program, the self-contained oil filled (SCOF) cable and the cross-linked polyethylene (XLPE) insulated cable. The SCOF cable is pressurized internally with oil and is successfully used in land applications. This type of cable did suffer from sleeving in the OTEC tests. The XLPE cable has not been successfully used in land applications in this country due to cable failures arising from small occlusions remaining in the polyethylene insulation. In the limited sample tests conducted by OTEC in a riser application, neither occlusion or any other failure was experienced. Nevertheless, industrial experience does not provide a sufficiently failure free data base on which to commit the use of an XLPE cable to an application requiring a low probability of failure over a 30 year design life. The development and testing of the OTEC riser cable will require a significant period of time if floating, 100 MWe sized OTEC's are the development goal.

Cold Water Pipe

The state of technology for the cold water pipe depends considerably on the size of the OTEC plant. The pipe for a 40 MWe plant reaching to 5° C water may be as large as 10 m (30 ft) in diameter; the pipe for a 10 MWe plant may be about 5 to 6 m; and the pipe for a 5 MWe plant may be 3+ m. In the larger size ranges, there is little or no data or expertise from other applications relevant to the design and deployment of an OTEC CWP.

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22 Simplex Wire and Cable Co., Final Report: Riser Cable Development for Ocean Thermal Energy Conversion Plants, June 1983, Portsmouth, NH.

Various materials have been investigated for the cold water pipe, including fiberglass reinforced plastic, steels, concrete and composites.[23] Continued research into materials and construction techniques for the cold water pipe are required for each different type of OTEC application. The most important design variation is between a pipe suspended from a floating platform or installed along the ocean floor. In either case, substantial forces will be imposed upon the pipe both during the installation process and during its operational life. The magnitude of these forces are sometimes difficult to determine.

The design of a vertical pipe and its suspension will depend largely upon the sea conditions to be expected over the life of the system as well as the characteristics of the platform from which it is suspended. Tests of a five foot diameter suspended pipe were completed in 1979 and the programs developed to predict load and moments were verified to provide adequate design accuracy. A ten-foot-diameter jointed section, representing a 1/3 scale suspended concrete cold water pipe, was tested to destruction and exceeded the design requirements for the 100 year storm by 40%.

In the case of a sea-floor-mounted cold water pipe, the loading forces imposed by waves and currents, the interface with the ocean floor, and the characteristics of the ocean floor are critical. There has been little work done on the securing of very large pipes to steep escarpments, or the measurement of the properties of these slopes and the design of adequate seafloor anchoring devices.

Tests are planned to instrument a section of an eight foot diameter pipe to be attached to a steep slope near the Seacoast Test Facility at NELH. Environmental measurements are to be taken concurrently with the measured loading and foundation forces. Instrumentation for measuring geotechnical properties will also be investigated.

Other Technical Factors

There are other technical problems that would have to be considered in the design, installation, and operation of commercial OTEC plants, including inspection, maintenance, and repair. These factors must be evaluated in determining long term financial feasibility. OTEC program efforts now are directed to reducing the primary OTEC technological risks, but other financial risks are equally important if the ultimate goal is to encourage private investment.

2. Alternative Systems and Applications

There are numerous alternatives to a so-called "standard" OTEC plant (i.e. a large, floating, closed-cycle plant feeding electrical power to a grid). Various combinations of alternative concepts, equipment, and sites provide different technological problems as well as opportunities for OTEC.

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23 Vega, L. et al., "Design, Fabrication and At-sea Test of a Large Scale OTEC Pipe, Joint MTS/IEEE Oceans '83 Conference, San Francisco, CA, August 1983.

Examples of alternative approaches include:

- o Plants of 40-100 MWe sizes for feeding power grids of large industrialized islands such as Puerto Rico and Hawaii;
- o Plants of 1 to 10 MWe for smaller islands;
- o Production of fresh water for Caribbean and other tropical regions;
- o Products, such as hydrogen, oxygen, ammonia, or magnesium, that can be made from the on site materials: sea water, air, and electricity;
- o Mariculture products, i.e., plants, fish, shellfish, using nutrient-rich OTEC deep water;
- o Chemical products, such as manganese (possibly using oceanic ores), aluminum and other energy intensive metals, and methanol, methane, and other fuels, that require feeder chemical stocks to be transported to the OTEC plant;
- o Variations of open cycle OTEC, including the Claude flash evaporator and the mist-lift systems; and
- o Use of geothermal, power plant waste, or solar pond heat to provide a heat source which, combined with a heat sink, could power a low temperature differential cycle similar to OTEC.

It appears that the development of the underlying technology for competitive, OTEC produced energy may continue to be the primary goal of the DOE OTEC program. However, interest appears to be gaining in smaller plants and specialty applications. Certainly the foreign efforts are in that direction at the present time. In many cases the technology for achieving these is available. It is generally believed, with a few exceptions, that small OTEC electric power plants are no more competitive in the market place than are the large plants, but, the small plants may provide certain experience and knowledge at less cost and risk.

Japan is presently concentrating on the development of 1 - 3 MWe plants. If they proceed as they have with the 100 kWe plants they have produced, these plants will initially be used to gain experimental data that might be applied to the construction of larger designs.

Smaller plants would be particularly attractive to the island communities that are not industrialized but are nevertheless highly dependent on imported fuels. For many islands, plants that also produce fresh water and/or provide fish development may be even more attractive.

Various combinations of the alternatives have been and are continuing to be investigated.

a. Open Cycle Systems

In the open cycle OTEC, warm sea water is used as the working fluid. The warm surface water is introduced into a low pressure evaporator where a small portion of the water flashes into water vapor. This vapor is used to drive a turbine and then is condensed by the cold deep sea water.

As was discussed earlier, the open cycle OTEC system is the system that Claude installed in 1929-1930 in Cuba. Neither was his system optimized nor was the technology available at that time to make the system feasible from an engineering standpoint.

There are two open cycle concepts receiving attention at the present time:

- The flash evaporator, "Claude cycle" system which generates water vapor for driving gas-vapor turbines.
- The two phase, mist generating system which produces a water head that can be used to drive a hydro-electric generator. There are several variations of the mist generator concept.

One other open cycle concept that has been analyzed is the foam system. Like the mist technique, the foam system produces a hydraulic head. It was eliminated from OTEC consideration due to the amounts and types of chemical (surfactants) that would be necessary to produce the foaming action necessary to develop the hydraulic head.

Claude cycle plants that use non-direct contact condenser heat exchangers, e.g., shell and tube, can also produce fresh water. Condensers using direct contact of the vapor from the turbine with the cold ocean water do not produce fresh water as a by-product. Mist and foam systems also do not produce fresh water.

Since 1977 there have been several investigations of open cycle OTEC. The main effort was the Westinghouse study completed in 1981, resulting in a 100 MWe concept believed to be competitive with closed cycle plants of similar output.[24] The system included an open channel flash evaporator; a demister; a 141 MWe single stage, vertical axis turbine generator; a shell and tube condenser; and a deaerator connected to the condenser venting. Several investigations have been undertaken in "Claude cycle" OTEC component areas identified in the Westinghouse study. These include: evaporators, condensers, turbines, and deaerators.

The Westinghouse concept used an open channel flash evaporator and a shell and tube condenser. Open channel flash evaporators are not particularly effective at the relatively low temperatures of warm sea water. The Solar Energy Research Institute (SERI) has been conducting research into falling jets and upward spouts for use in evaporators and falling jets for use

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24 Coleman, W. H., "Westinghouse OTEC Power Systems," Energy V 5, pp. 493-501, 1980, Pergamon Press.

in direct contact condensers.[25,26] Early limited testing has been conducted at SERI and tests using sea water have begun at the Seacoast Test Facility in Hawaii.

Critical to all open cycle systems is the availability of deaerators because there are considerable amounts of dissolved gases in sea water, principally nitrogen and oxygen. If these gases are not removed from the water either before or after vaporization, they will build up in the condenser and make the condenser inoperative after a short while. The percentage of the dissolved gases that will come out of solution and affect the condenser will vary depending on the design of the heat exchangers, operating conditions, and characteristics of the water. Estimates have ranged from a few percent by the French,[27] to 30% by the Oak Ridge National Laboratory (ORNL)[28] to 80% by Claude, and similar high values by Westinghouse. Deaerators can be used both in the evaporator and condenser stages of the system to remove these gases.

Several types of deaerators have been investigated by ORNL including the barometric intake deaeration concept which was incorporated by Claude in his 1929 installation on Cuba.[29] ORNL theoretical and laboratory studies have indicated that the combined use of pre-deaeration using the Claude concept and condenser deaeration by compressing the noncondensibles and reinjecting them into the warm water effluent should be considered in any open cycle design. The development of deaeration technology is still critical to successful open cycle OTEC operation.

Considerable effort would be necessary to develop a large diameter single stage turbine for a large open cycle OTEC. One approach would use helicopter and wind turbine blade technology. The French are considering the use of the lower pressure stages of a large steam power plant turbine for small 5 MWe OTEC plants.

As a result of technology advances in components for a Claude cycle OTEC, a contract has been awarded to the Florida Solar Energy Center, with Creare, Inc., of Hanover, N.H., as the principal subcontractor, to review the

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25 Bharathan, D., Kreith, F., and Owens, W. L., "An Overview of Heat and Mass Transfer in Open Cycle OTEC Systems," ASME/JSME Thermal Engineering Joint Conference Proceedings, V2, ASME, Mar. 20-24, 1983, New York, NY.

26 Bharathan, D., and Penny, T., "Flash Evaporation from Turbulent Water Jets," ASME/JSME Thermal Engineering Joint Conference Proceedings, V2, Mar. 20-24, 1983. American Society of Mechanical Engineers, New York, NY.

27 Rey, M., Lecoffre, Y., and Poux, J., 1980, "Open Cycle Seawater Evaporation and Gas Venting Studies," Conference Proceedings, 7th Ocean Energy Conference, June 2-5, 1980, Washington, D.C.

28 Chen, F. C., and Golshani, A., "OTEC Gas Desorption Studies," Journal of Solar Energy Engineering, February 1982, V 104, pp. 35-40.

29 Ibid.

optimization of Claude open cycle OTEC systems and to prepare a cost analysis of the resulting system.

The mist-lift, open cycle OTEC concept eliminates both the surface type evaporators and condensers as well as the gas turbines required in the Claude cycle OTEC.[30] Instead, the warm ocean water is forced through small holes and the resultant mist is sprayed upward into the lower portion of an evacuated vertical duct. Vapor is flashed from the spray and "drags" (lifts) the remaining droplets upward to the top of the duct. At the top the water vapor is condensed using direct contact with the deep cold water. The condensed water vapor and the lifted droplets then flow downward through a hydro-electric generator. The theoretical equivalent potential lift from the thermal energy is 104 meters. However, the net working height that could be produced by such an OTEC is estimated to be between 79 to 100 meters for warm and cold oceanic waters having a temperature differential of 20° C.[31,32] Sea water tests, to demonstrate the lift concept, were conducted by R & D Associates of Marina del Ray, CA., at the Seacoast Test Facility in Hawaii in September, 1983. A lift of 25 meters was achieved in these tests in the experimental system with a temperature differential of only 17°C. Deaerators are also required in the mist open cycle systems to prevent the build-up of non-condensibles in the direct contact condenser. While preliminary experimental results are encouraging, the practicality of the mist system is not yet proven.[33]

b. Solar Pond/OTEC Concept

The solar pond/OTEC concept combines two concepts -- the closed cycle OTEC and the solar pond. The combination of these two concepts is being investigated by the Argonne National Laboratory[34] and by SETS, Inc. in Hawaii.

A solar pond located in tropical regions stores energy in stratified layers of salt water, with the salt concentration varying from approximately a sea water concentration of 3% near the surface to 24% near the bottom. The increasing density associated with the increasing salt concentration results in a stable stratification provided that the pond is not stirred or mixed by

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30 Chen, F. C., and Michel, J.W., "Development of the OTEC Lift Cycles," 7th Ocean Energy Conference, June 2-5, 1980, Washington, D.C.

31 Mist-Flow OTEC Process, Project Summary, R&D Associates, Report of the Proceedings of the OTEC Alternate Cycles Contractors' Information Exchange Meeting, sponsored by the U.S. Department of Energy, December 1978.

32 Development of the Mist-Flow Process, RDA Proposal 583002, R&D Associates, February 1983, Marina del Ray, CA.

33 Meridian Corp., "Ocean Energy Technology Assessment," 1983.

34 Argonne National Laboratory, "Scoping Study for a Combination Solar Pond/OTEC Plant for Generation of Electrical Power," Argonne National Laboratory, July 1, 1982, Argonne, IL.

waves. Three zones of stratification develop in such a pool. The top zone is a thin convective layer. The middle zone is a non-convective layer and is relatively motionless. This layer provides insulation for the bottom zone. The bottom zone, the primary heat storage layer, is also a convective layer. Cellular motions develop in this layer. The bottom and sides of the pond must be sealed to prevent the salt solution from passing into the ground.

The very salty bottom layer has a large heat capacity and, depending upon the design and operation, the temperature of the layer may become as high as 100° C. The salt water brine is drawn from the top of this lower layer and is used in a closed cycle loop to evaporate a working fluid, such as Freon. The brine is then returned to the bottom of the lower stratified pond layer. The vaporized working fluid drives a turbine generator, is then condensed by cold, deep ocean water, and then is returned to the evaporator to be recycled. Theoretical estimates for such a closed cycle system using a 75° to 95° C water temperature differential indicate that it could have an overall cycle efficiency of better than 11% as compared to a few per cent for an OTEC system using the smaller temperature differences between surface and deep ocean waters. Thirty acres of 3 meter depth pond would be required to provide 1 MWe. For small plants, there are few technical problems other than preventing mixing by waves and the usual cold water pipe problems. Because of the higher efficiency, however, a much smaller volume of cold water flow is required than for a similar output OTEC system. Salt, incidentally, is not a small cost. A major consideration is the land requirement and the resultant costs of the ponds. Sites in Hawaii and Jamaica have been proposed for solar pond/OTEC systems. A solar pond has been operating at Cabo Frio near Buenos Aires, Brazil for over 10 years. The State of Hawaii has funded the detailed design of a one-acre "SPOTEC" demonstration pond to be built at NELH, which would use the existing cold water supply.

c. Fresh Water Production

The open cycle OTEC plants that use non-direct contact condensers, such as the shell-and-tube, are capable of producing fresh water condensate. Numerous analyses have been made of fresh water production. In general, open cycle OTEC plants that produce only fresh water are not cost competitive with other desalination schemes. Large, open cycle plants that produce electricity and fresh water are, at present, technologically deficient because of the lack of large capacity, low pressure gas turbine technology. Non-contact condensers required for freshwater production are also significantly less efficient for electricity generation than direct-contact condensers.

The composite open cycle-closed cycle OTEC is an alternative suggestion for providing fresh water while avoiding the problems of low-pressure vapor turbine. The composite open-closed cycle fresh water plant would use the open cycle loop for producing fresh water. The closed cycle portion would produce the electrical power required for running the warm and cold sea water pumps and other auxiliary equipment for the open cycle loop as well as for the closed cycle loop. A preliminary cost analysis indicated that the composite plant might be competitive with fossil fuel fired flash evaporators for

producing fresh water from sea water.[35] A fresh water producing OTEC plant has been suggested for the U.S. Virgin Islands as well as other water deficient tropical islands. Only a cursory analysis of the fresh water producing, composite cycle OTEC plant has thus far been made.

d. OTEC/Mariculture

Conceptual designs for OTEC systems often include a mariculture component, using the cold, nutrient rich deep sea effluent to grow food or biomass products. The cold water effluent, considered a "waste product" from the OTEC system, has many characteristics which make it a valuable resource for mariculture. Deep ocean waters contain higher levels of inorganic nutrients (e.g., nitrate, phosphate) than surface waters. The nutrients are a necessary and, in many instances, a growth limiting factor for marine phytoplankton and macroalgae, the "primary producers" in marine ecosystems. In tropical regions, the cold temperature of the deep water can provide a suitable habitat for potentially marketable, non-indigenous species of plants and animals. In addition, by controlling the mixing of the cold water effluent with warmer surface water, a wide range of temperatures can be achieved and held constant or modified as desired. Large volume flows are advantageous for many mariculture systems by providing flushing of organic wastes and reducing the likelihood of disease transmission. Thus, higher density cultures can be maintained. Finally, deep ocean water contains significantly fewer bacteria and other microorganisms which can cause disease or contamination in cultures. Concentrations of chemical "pollutants" will also be lower in deep ocean waters than in near shore surface waters. Thus, mariculture has appeared to many to be a natural adjunct to OTEC systems.

OTEC proposals incorporating mariculture have focused on shore-based OTEC systems and include land-based "tank farms" or the utilization of adjacent lagoons as containment mechanisms. Open ocean mariculture/OTEC systems have also been discussed[36] but are a more long-term application, both because the development of open-ocean OTEC systems lags behind shore-based systems, and because there is relatively little experience with open ocean "farming." The engineering problems of temperature control, separation of effluents, and containment of organisms are greater in the more open environment.

There is considerable experience and expertise with a wide variety of land-based aquaculture systems, much of which is applicable to shore-based OTEC operations. However, given the complexity of biological variables and the sensitivity of cultured organisms to environmental conditions and water quality, any mariculture operation would require site specific testing with the organisms to determine actual growth rates, density factors, mortality rates, etc. Opportunities to conduct this type of research for OTEC related projects are limited by the availability of facilites actively pumping deep cold seawater with the necessary containment and monitoring facilities.

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35 Coffay, B. and Rabas, T. J., 1981. "A New and Viable OTEC Application," 8th Ocean Energy Conference, Washington, D.C., June 1981.

36 Werner, E. 1981. "An Integrated OTEC-Mariculture System"; 8th Ocean Energy Conference, Washington, D.C.

A major concern in linking mariculture to OTEC systems is the reliability of the water supply. Any disruption of the cold water supply system, whether for routine maintenance or due to equipment failure, is potentially disastrous for a mariculture operation where an entire crop could be lost.[37] Depending on the types of species used, the problem may be manageable for land-based operations by providing back-up refrigeration and recirculation systems. In addition, redundancy in pumping systems and modularity in OTEC power systems may reduce the likelihood of interruption of the cold water supply.

A currently active facility providing sufficient quantities of cold seawater for mariculture is the Natural Energy Laboratory of Hawaii at Keahole Point on the Island of Hawaii. Organisms grown there include salmon and trout, Nori (seaweed popular in Japanese diet), lobsters, and abalone. Results in terms of growth rates, production values, and protein content have been good to exceptional.[38] The private concern sponsoring the abalone work presently is considering developing a commercial demonstration production facility at the Keahole site. Reasons for success are attributed to the ability to provide flexible, accurate, and consistent temperature control, high volume flow rates, and seawater that is relatively free of biological and chemical contaminants.

Dr. Oswald Roels of Maritek Corporation has conducted research using artificially upwelled deep seawater for growing a variety of marine plants and animals. He has concluded that the combination of mariculture and OTEC is not presently economically viable.[39] One reason is that a greater market exists for tropical species unsuitable for growing in cold water. The Maritek Corporation is currently operating a production facility for hatching and growing shrimp in the Virgin Islands using artifically upwelled deep seawater, but the water is allowed to warm up before it is used.

Another major research effort that has taken place over the past five years with applications relevant to OTEC systems is the experimental work on kelp farms off the California coast using artificially upwelled nutrient rich water. These experiments have included both an open ocean test structure with upwelling pumps and near-shore test beds.[40]

Future development of mariculture in conjunction with OTEC will depend largely on the economic return. The natural synergism between the requirements of the two systems suggests that their combination would make

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37 R. Cohen, 1982. "Energy from the Ocean," Phil. Trans. R. Soc. Lond. A 307:405-437.

38 Telephone conversation, Dr. Thomas H. Daniel, Laboratory Director, the Natural Energy Laboratory of Hawaii, October 1983.

39 Telephone conversation, Dr. Oswald Roels, Maritek Corporation, October 1983.

40 For a description of these experiments, see "Energy From Open Ocean Kelp Farms" prepared by OTA at the request of the Senate Commerce Committee, Committee Print, September 1980.

both ventures more economically attractive. The requirements for mariculture would increase the engineering and manpower requirements as well as capital costs for "plumbing," containment structures, and monitoring and harvesting equipment. For land-based systems, there also is an additional commitment of land area. The gross economic return depends largely on biological parameters, such as production rates, as well as market factors. One assessment[41] of the technical and economic feasibility of combining OTEC and mariculture concluded that phytoplankton, macroalgae and shellfish were potentially viable products, while finfish production appeared to be less feasible. Another study[42] concluded that the economic return from raising salmon for the Hawaiian restaurant market in the effluent of a 60 MW OTEC plant could be much larger than the return from the energy product.

In general, it appears that on a worldwide basis, mariculture technology is well established and will continue to develop regardless of its connection with OTEC. On the other hand, the development of OTEC systems is less advanced and will depend on as yet unproven economic feasibility. To the extent that combining OTEC with mariculture may make OTEC ventures viable, economic feasibility studies should include an analysis of this potential.

e. OTEC Plantships

Electrical power is not transportable from OTEC plants sited in ocean areas distant from land. The major part of the OTEC resource exists in such areas, however, and alternative energy intensive products and fuels have been suggested as appropriate outputs from floating plants. The products would be transported to market by ship from the tropical sites of moored or grazing OTEC plantships.

Conceptual studies of a number of OTEC plantships have been conducted by the Applied Physics Laboratory of The Johns Hopkins University and others. Products that have been proposed by various investigators for the plantship operation include: methanol, ammonia, aluminum, bromine, chlorine, ethylene, hydrogen, magnesium, manganese, nitrogen, and oxygen.

Methanol is the most recently considered product and was investigated by APL/JHU in conjunction with Brown & Root Development, Inc.; Rockwell International; and Ebasco Services, Inc.[43] In the process proposed, hydrogen and oxygen are produced by the OTEC plant by electrolysis. The oxygen is reacted with a slurry coal which is transported to the plantship on a routine

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41 S. Bailey and L. Vega, 1981. "Assessment of OTEC-Based Mariculture Operations," 8th Ocean Energy Conference, Washington, D.C.

42 State of Hawaii Dept. of Land and Natural Resources, June 1981, "Mariculture and Ocean Thermal Energy Conversion State-of-the-Art Assessment," Honolulu, Hawaii.

43 Avery, W. H. and D. Richards, "Design of a 160 MW OTEC Plantship for Production of Methanol," Applied Physics Laboratory, The Johns Hopkins University, Joint MTS/IEEE Oceans 83 Conference, Aug. 29-Sept. 1, 1983, San Francisco, CA.

schedule. The resulting carbon monoxide is catalytically combined with the hydrogen to produce methanol which is transported back to the U.S. by ship. The advantage of this proposal is the large reduction in the coal needed compared to a conventional coal-to-methanol plant. One reason is that the hydrogen is obtained from electrolysis of water using OTEC, and not from a reaction between coal and water as is the case for the conventional plants. A reduction in coal requirements of over 55 percent is possible. In the first analysis of the process a Texaco gasifier was used. A second iteration of the process will consider the use of a molten carbonate gasifier. The preliminary estimate of the sales price of methanol for a plant yielding 166 million gal/yr is between $.55 to $.72 per gallon at the receiving U.S. port, equivalent to an unleaded gasoline price of $0.73 to $0.96 per gallon in terms of energy content.

While OTA was not able to carefully review this analysis, APL/JHU investigators believe that the OTEC methanol concept is commercially attractive. They also believe that critcal OTEC technologies (i.e., the large suspended cold water pipe), as well as technologies critical to the methanol process, will need multi-year research to bring the technological and investment risk factors down to levels that will encourage private financing.

Undoubtedly other energy intensive secondary products besides those listed could be found that might be suitable for OTEC plantship operations. Several industrial companies have conducted studies of OTEC chemical plantships, generally with DOE funds. However, industry has not made funding commitments that would be necessary for such plants to come into existence. The reasons for such non-commitment are likely two-fold: market factors and OTEC technological risks, principally the cold water pipe and additionally the turbine in the case of the Claude open cycle OTEC. Unless an extremely promising market situation were to unfold, it is unlikely that industry will invest in OTEC plantships until the technological risks are significantly reduced.

f. Bottoming and Enhanced OTEC Alternatives

Conventional steam power plants, both fossil and nuclear powered, dump considerable amounts of low grade heat with their cooling water effluent. If other, cooler water were available, one could build bottoming cycle plants to generate additional electricity. Suggestions have been made to use some of the technology developed for OTEC to provide cooler oceanic water for coastal power plants.[44] Similar OTEC-like plants have been suggested for the exploitation of low temperature geothermal sources.

While bottoming cycle technology is a possible energy production technique, the use of OTEC technologies has not been addressed to any great degree by power companies because of the limited supply of coolant water. To extract energy from the power plant effluent, some lower level heat sink is required. In general the use of the available heat sink, the water source from which the plant's cooling water came from, has been optimized and already

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[44] Chen, F. C., "Land-Based Application of an OTEC Open-Cycle Power System," 6th OTEC Conference, June 19-22, 1979, Washington, D.C.

committed. The vast amounts of additional water that would be required for an OTEC bottoming cycle thus are not generally available or not available at a reasonable cost. For specific nuclear plants, however, bottoming cycles have been considered but market and other factors have not been present which would make the extraction attractive.

For those oceanside steam plant locations that are also suitable for OTEC sites, the possible use of steamplant effluents for enhancing the ocean surface water temperatures may be a way of improving the efficiency of an OTEC plant.

The Ocean Thermal Corporation's plan for the Pilot Plant project includes steam power plant enhancement. The Preliminary Design Study is to incorporate thermal enhancement from the Hawaiian Power Company plant at Kahe Point.

The use of geothermal heat sources for the enhancement of OTEC warm sea surface water would also be very site specific. The geothermal energy, the near-shore OTEC ocean energy resources, and the market for the power must co-exist. There are few locations which would satisfy those requirements.

g. Low Temperature Geothermal Alternatives

There are locations where the geothermal temperatures are not sufficient to satisfy the requirements of a superheated steam power plant but are sufficient for OTEC-like closed cycle systems and are near a source of cold water. One such location is at Adak, Alaska, located in the Aleutian Island chain.

The Applied Physics Laboratory, in cooperation with the Naval Civil Engineering Laboratory and the Naval Weapons Center at China Lake, CA., has conducted a preliminary concept analysis for an Adak located, OTEC-like, geothermal power plant.[45] Such a plant could satisfy much of the energy requirements for base operations of the naval base on Adak where the cost of fuel is considerable. Other factors, including the types of fuel used at the base, add to the credible use of the available low temperature geothermal resources.

A dual binary closed cycle plant has been analyzed. The high temperature loop of the system uses water as the working fluid; the low temperature loop of the system uses ammonia. A preliminary analysis of a single loop system has indicated that the dual system is probably more effective.

The results of the preliminary analysis of the Adak location have been sufficiently promising for the Navy to award a contract to TRW, Redondo Beach, Calif., to conduct an in depth feasibility analysis which is expected to be completed early in 1984. Should the analysis results be positive, the Navy

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[45] Dugger, G. L., Perini, L. L., Richards, D., and Paddison, F. C., "The Potential for a Hybrid Geothermal-Ocean Thermal Energy Conversion (GEOTEC) Power Plant Installation at Adak Island, Alaska," 18th Intersociety Energy Conversion Engineering Conference, Aug. 21-26, 1983, Orlando, FL, American Institute of Chemical Engineers.

may undertake further exploratory drilling to assess the geothermal source. While other geothermal locations may exist that would match Navy needs, the Adak location is the most promising.

Hawaii is developing electrical generating plants that will utilize its high temperature geothermal resources. There are probably low temperature geothermal energy resources on the islands and at other locations in Alaska and the U.S. west coast that might be extracted using the dual binary system proposed for Adak.

OTEC MARKETS AND ECONOMICS

1. Market Considerations

The fundamental requirement for a commercial OTEC plant is proximity to an ocean region with a temperature differential of 20° C or more over a depth of 1000 meters or less. A survey done in 1981 for the U.S. Departments of State and Energy identified 98 nations and territories having access to such resources within 200 miles of their coastline.[46] Of this number, three were developed nations - the United States, Australia (of course only those parts of these countries near the warmer latitudes) and Japan, 29 were territories of developed nations, and 63 were developing nations with market economies.

This physical requirement, of course, is only the first of many criteria that must be satisfied before an OTEC device can be considered an economically attractive candidate for generating baseload electric power. Among other important criteria are that their electricity costs are very high. When viewing the choices mentioned above in this light, of the developed countries only Japan remains. The United States mainland and Australia have vast coal resources that likely would preclude their commercial use of OTEC for a very long time. Of course, if coal combustion should become unacceptable, the situation could change somewhat. Even then, however, both countries have other options, such as nuclear, that probably make OTEC doubtful for any application to the mainland of each country. Japan, while having no significant energy resources, has embarked on a large program of building nuclear power plants. Therefore OTEC would have to compete with these facilities for future electricity supply. Unless a substantial reduction in OTEC costs is achieved, it appears that nuclear would be cheaper for the indefinite future for Japan.

If the developed countries are unlikely candidates, we must turn to the developing nations and territories. These areas include the Pacific Trust Territory, American Samoa, Guam, the Virgin Islands, and Puerto Rico (all territories of the United States). These islands essentially are completely dependent on imported oil for their energy needs for both electricity generation and transportation. The State of Hawaii shares these characteristics. In 1980 the 63 developing countries plus 4 U.S. territories (Pacific Trust Territory, American Samoa, Guam and Virgin Islands) had an

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[46] L.E. Dunbar, "OTEC Market Potential in Small Pacific Islands," International Conference on Ocean Resource Development in the Pacific, October 1981, Honolulu, Hawaii.

installed electric generating capacity of about 70,000 MW and used about 2.5 million barrels per day of oil for all purposes including 1.35 million barrels per day for electricity generation (assuming a capacity factor of 50%).[47,48] Currently electricity prices in Hawaii are from 10 to 20 cents per kWh.[49] The cost of electricity on smaller, remote islands, such as in the Pacific Trust Territory, has been estimated to be as high as 50¢/kWh.[50]

Assuming a growth rate of 3 percent per year for electricity generation, capacity additions of 100,000 MW would be needed in the next 30 years. In addition, a fraction of currently existing capacity would be retired and must be replaced. If oil is used to fuel the added capacity at a 50% capacity factor, an additional 1.9 million barrels per day would be needed at the end of the 30 year period. This new capacity also will have to be added in relatively small increments because the current capacity consists of a large number of small (a few to a few tens of MW) systems. Guam, for instance, has a capacity of 314 MW while Hawaii's 1981 capacity was 1,300 MW.[51,52] Increments of one to 40 MW will be typical of the size of new plants added over the next several years in many of these regions.

2. OTEC Contribution

It is this set of conditions - high priced electricity and demand growth that will require small additions of generating capacity - that OTEC and other possible alternative energy systems will face if they attempt to compete for the electric generating market in tropical island areas. In addition, OTEC has been proposed as a means to produce hydrogen for synthetic fuel production, primarily methanol[53] and ammonia. To produce methanol requires a source of carbon which is likely to be coal. Tropical oceanic regions have very little coal resources, so the coal must be imported. The cost differential per Btu between imported oil and imported coal to these areas appears to be large enough to make this a possibility. If this feature were to prove attractive, it could open up the liquid fuel market to OTEC as well.

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47 Ibid.

48 1981 International Energy Annual, U.S. Department of Energy, Washington, D.C., September, 1982, pp. 28-29.

49 Typical Electric Bills-January 1, 1982, U.S. Department of Energy, Washington, D.C., October 1982.

50 Territorial Energy Assessment, Final Report, U.S. Department of Energy, Washington, D.C., December 1982.

51 Dunbar, "OTEC Market Potential in Small Pacific Islands," 1981.

52 Electric Power Annual, U.S. Department of Energy, Washington, D.C., November 1982.

53 Avery and Richards, "Design of a 160 MW OTEC Plantship for Production of Methanol," 1983.

Developing reliable estimates of the cost of producing electricity from OTEC is, of course, one of the principal objectives of the research and development. A number of researchers made preliminary estimates, however, and we will use those to see how OTEC might fare against other options to supply electric energy and/or synthetic fuels to these developing countries and trust territories. We must emphasize that these cost estimates are based on paper studies and not on working machines. In Figure 1 a cost curve is displayed showing cost per kW as a function of electric power output.[54] The most striking feature is the steepness of the curve. If this is borne out in practice, it indicates a very high economy of scale factor. Other estimates of costs for small OTEC machines, 10 MW and less, agree with the lower bound of the curve in the figure. Using this curve, it can be seen that the estimated cost range for OTEC devices suitable for the developing country market (of about 10-100 MWe sizes) is about $4500 to $12,000 per kW. Using assumptions about the capacity factor and operation and maintenance costs from reference 54, and assumptions from the EPRI Technical Assessment Guide about capital recovery factors, these capital costs translate into levelized electricity costs over 30 years of 9.1 to 24.1 cents per kWh.[55,56]

Another analysis was performed to estimate the cost of producing methanol from a combination OTEC and coal-to-methanol plant.[57] A major consideration with this approach is that larger OTEC machines can be used since any excess methanol can be shipped to other markets which is not feasible for excess electricity from OTEC. By using large OTEC devices, the authors argue that economies of scale for OTEC will translate into a low capital cost. The analysis used a 160 MW OTEC system and a methanol plant that produced 166 million gallons per year. This facility required 1210 metric tons of coal per day. (By way of comparison, a conventional coal-to-methanol plant producing this quantity of methanol would require 2700 metric tons of coal per day). The analysis assumed that mortgage guarantees and tax credits would apply to lower the annual costs. For this system, sales prices of methanol delivered to the U.S. ranging from 55 to 72 cents per gallon were estimated. Based on vehicle mileage comparisons, such prices correspond to unleaded gasoline at 73 to 96 cents per gallon.

3. Competitive Concepts

In the next 10 to 20 years, the major competitor to one to 40 MWe sized OTEC electric plants will be combustion turbines or diesels fueled by distillate fuel oil. This is the current source of electricity for nearly all of the regions where OTEC is now proposed. Other technologies are available, such as coal or wood-fired steam turbines, and wind machines. The former,

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54 Dunbar, "OTEC Market Potential in Small Pacific Islands," 1981.

55 Ibid.

56 Technical Assessment Guide, Electric Power Research Institute, Palo Alto, CA, May 1982.

57 Avery and Richards, "Design of a 160 MW OTEC Plantship for Production of Methanol," 1983.

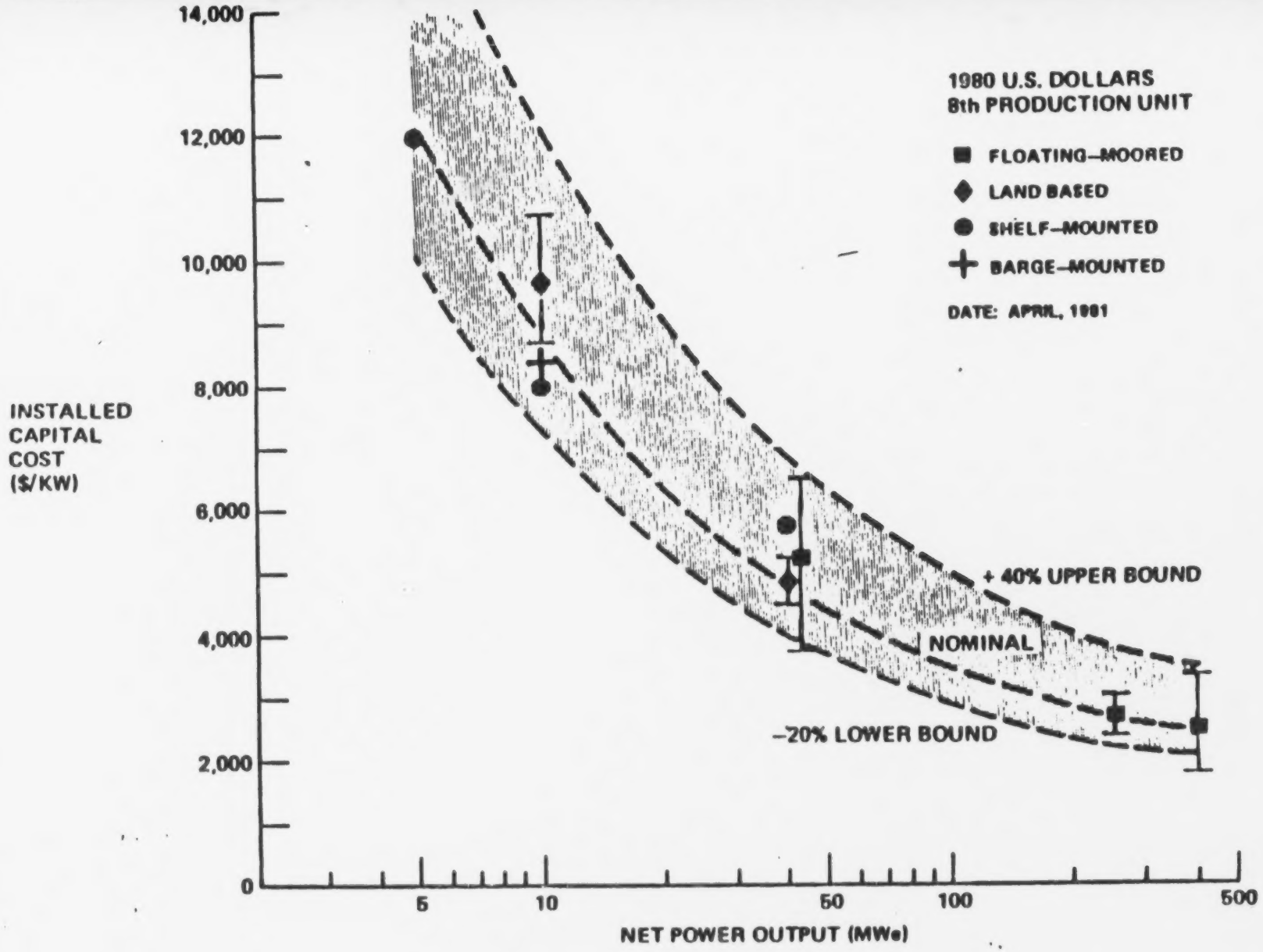

Figure 1: OTEC Plant Capital Costs

Source: Dunbar, L. E., "OTEC Market Potential in South Pacific Islands," International Conference on Ocean Resource Development in the Pacific, October 13-15, 1981, Honolulu, Hawaii.

however, are more costly per unit of power than combustion Turbines at the sizes we are concerned with; and the latter, which are also very costly per KWH, cannot provide baseload power by themselves. Although the prices calculated for the larger OTEC plants (greater than 40 MW), are somewhat lower than current electricity prices in most of these regions, it is not correct to make this comparison in order to determine whether OTEC will be competitive. OTEC is a baseload technology and a very high capacity factor was assumed in the above calculations (85 percent, see reference 54). The capacity factor of most of the electric utility systems in these regions is much lower. The correct comparison is with a conventional device also operated as a baseload unit. Currently, a 10 MW combustion turbine will cost about $300 per kW while a 10 MW diesel will cost about $500 per kW.[58] The former operates at an efficiency of about 30% while the diesel operates at an efficiency around 38%.[59] Operating either as a baseload unit under the same conditions as OTEC, and with a current fuel price of $6.00 per MMBtu for distillate fuel oil (assumed to grow at a rate of 6% per year according to reference 54), we arrive at an electricity cost of 14.2 and 11.2 cents per kWh respectively. These are considerably lower than the costs from the 10 MW OTEC. Because fuel costs are so dominant for the combustion turbine and diesel, the cost of electricity from a 40 MW combustion turbine or diesel is nearly the same as from the 10 MW units. Therefore a 40 MW OTEC unit under the assumptions discussed above would produce less costly electricity.

Beyond the 10 to 20 year horizon, however, other technologies are likely to be available. The most likely are advanced coal combustion devices, such as fluidized bed, which allow coal to be used directly with combustion turbines, methanol produced from coal in coal-rich regions, and small nuclear power plants. We have not examined all of these but we have prepared some cost estimates of the methanol option which will provide a benchmark for the competition that OTEC will find in attempting to penetrate these markets. In the OTA assessment on synthetic fuels, we calculated a 30 year levelized cost (i.e., including escalation due to real and inflationary increases in the cost of production) for methanol from coal of about $9.00 per MMBtu[60] (about 57¢ per gallon). To this must be added the cost of transportation. Currently this is about 6 cents per gallon or about 95 cents per MMBTu[61] (assuming high-volume, trans-ocean, large ships and terminals). If used in a combustion turbine or diesel under the same assumptions cited on page 50, electricity costs of 13.6 and 10.5 cents per kWh are obtained. At 40 MW these costs will be somewhat lower, but still in the vicinity of 9 to 12 cents per kWh. An additional possibility with these methanol systems is the use of combined

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58 Industrial and Commercial Cogeneration, Office of Technology Assessment, U.S. Congress, Washington, D.C., February 1983.

59 Ibid.

60 Increased Automobile Fuel Efficiency and Synthetic Fuels; Alternatives for Reducing Oil Imports, Office of Technology Assessment, U.S. Congress, Washington, D.C., September 1982.

61 Methanol vs. LNG in International Trade, Jensen Associates, Washington D.C., November 1980.

cycle combustion turbines which have much higher efficiences. Values of 50% should be achieved by the 1990s.[62] If so, electricity costs from these systems using methanol from coal can drop below 9 cents per kWh. These costs are well within the range projected for OTEC and have the additional advantage that the technology is much more proven than OTEC. Offsetting this advantage is the fact that coal is required. Therefore this option is limited by the coal resource base as well as any environmental problems limiting coal's use. Ultimately, methanol can be produced from biomass - wood, grasses and crop residues - but this method is more costly and the ultimate world biomass renewable resource base may not be sufficient to support all of the world's liquid fuel requirements.

Finally, if this methanol option proves successful, it will affect the opportunities for OTEC as a producer of synthetic fuels. The cost of methanol from coal for proposed mainland U.S. projects, including transportation charges, is estimated to be about 63 cents per gallon. This is within the range of estimates calculated for the proposal to produce methanol from a combination of coal and hydrogen plus oxygen produced by OTEC.[63]

4. Financial Considerations

While we were unable to determine the detailed financial capabilities of the various developing nations and territories which are candidates for OTEC, in general, they do not have the resources to finance an OTEC plant without outside help. The issue then, is whether the outside entities are willing to take the risk necessary to finance an OTEC plant compared to a more traditional plant such as a combustion turbine. Currently, this does not seem to be the case. One island nation has been attempting to obtain OTEC investment capital from a wide variety of sources including aid programs of several nations, the World Bank, UNDP and other international agencies, and private sources without success. The risk of OTEC is apparently too high for any of these potential investors to take action at this time. This was confirmed in a conference on energy planning for U.S. insular territories sponsored by the Congressional Research Service.[64] There it was pointed out that a return on investment of 25 to 30 percent after tax was required before private investors would be willing to invest in a new solar technology compared to a 15 to 20 percent return for a more proven technology such as hydroelectric generation.

At a minimum, therefore, it appears that full-scale demonstrations of OTEC will be needed before any so-called traditional investment is forthcoming. Before then, it may be possible to secure financing if the loans

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62 See, for example, General Electric Co., Gas Turbine Division, Schenectady, NY.

63 Avery and Richards, "Design of a 160 MW OTEC Plantship for Production of Methanol," 1983.

64 "A Summary of Issues at the Conference on Energy Planning and Implementation in the U.S. Insular Areas," Congressional Research Service, The Library of Congress, Washington, D.C., Oct. 11, 1983.

are guaranteed and if part of the cost is paid by the government. None of the developing countries, however, have adequate resources by themselves to meet these conditions. Therefore, it appears that larger nations would have to be the source of funding for the first plants, and they would do this as part of an economic development package. The latter motive appears to be the reason for the current Japanese interest in providing funds for OTEC construction to developing nations.

A recent study[65] has concluded that, with current financial incentives for first-of-a-kind OTEC plants, the after-tax financial return from a 40-60 MWe plant, either generating electricity to be cabled ashore or producing methanol, would meet criteria for successful financing of maritime ventures. The major financial incentives available to U.S. companies for commercial OTEC development are Title XI loan guarantees and a 15% business energy investment tax credit. PL 96-320, the OTEC Act of 1980, amended Title XI of the Merchant Marine Act, 1936, to authorize loan guarantees of up to 87.5% of the construction cost of OTEC facilities owned by U.S. citizens. A special $2 billion subfund was authorized for this purpose to guarantee loans for up to 5 separate projects, or a total of 400 MW capacity, whichever comes first. The business energy investment credit for OTEC was included in the Crude Oil Windfall Profits Act (PL 96-223). A 15% tax credit is available for OTEC equipment placed in service by December 31, 1985. The tax credit is available only for OTEC equipment at two locations to be designated by the Secretary of the Treasury. The equipment must be used to generate energy for use in the U.S. (the 50 states and the District of Columbia).

The study cited above assumed that the tax credit provisions would be extended through the 1990's and that use of the loan guarantees would be allowed by the Administration.

Even though, to date, no U.S. company has made use of these incentives for an OTEC venture, some proponents of OTEC are concerned that such programs receive continued Federal support and even promotion by Federal agencies. Some have also suggested that OTEC incentives be extended to U.S. territories as well.

While OTEC financial incentives will certainly improve chances of private investment in this technology, they must also be evaluated considering the best use of national resources and incentives available for other alternative energy technologies.

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65 A Financing Option: The Effect of Financial Assumption Variables on the Economics of Ocean Thermal Energy Conversion, Draft, prepared by Argent Group, Ltd., Bethesda, MD, for The Johns Hopkins University, November 1983.

Appendix A

Summary of DOE-Sponsored OTEC R&D Projects

as of September 1983

CURRENT R&D PROJECTS SUPPORTED BY DOE

1. Argonne National Laboratory - FY83 Funding: $1,100,000

Biofouling, Corrosion and Materials Testing

The research effort in biofouling, corrosion, and materials is centered in three major areas at this time: (1) biofouling on surfaces enhanced for heat transfer; (2) biofouling countermeasures with minimized chlorine concentrations and (3) the identification and development of materials that are potentially attractive for OTEC applications but which are not normally used in marine environments.

Two recent notable accomplishments were the operation of a cold-water loop for 300 days with no evidence of biofouling buildup, and the operation of a warm-water loop without fouling for two years. Aluminum cladding and coating tests have been started, as have chemical biocontrol tests with minimal chlorine concentrations.

Heat Exchanger Development

This project is to develop general specifications for compact heat exchangers for low-grade heat-transfer applications.

General guidelines have been developed for selecting the geometry of OTEC exchangers for different systems designs.

Studies aimed at optimizing the geometries for various types of heat exchangers have been started. For water-side channels, the length and equivalent diameter will be optimized for both circular-tube and square/rectangular channel designs. For ammonia-side channels, similar optimizations will be made for Trane-type and plate-type compact heat exchangers.

II. Applied Physics Laboratory - FY83 Funding: $300,000

Wave Energy Conversion

The viability of the design, potential practical applications and use, and commercial potential and costs will be determined.

A simulation model has been developed and is being used to investigate load/speed control systems, etc., and will provide the basis for design verification and test data interpretation.

Geothermal OTEC

This joint project with the U.S. Navy is intended to develop hybrid power plant concepts that combine geothermal and OTEC technologies to best advantage, thereby yielding economical power generation from geothermal resources of marginal quality.

This includes development of generic GEOTEC plant concepts that are applicable for both civil and military sites. Pursuant to these objectives, cycle analyses and plant cost estimates have been completed for plants on the U.S. West Coast. A conceptual design for an Adak, Alaska site is underway. Conceptual designs for generic systems, directed at optimization for a geofluid source of less than 120°C, are planned.

OTEC Methanol

The potential merits of OTEC-Methanol synthesis, with on-board gasification of coal integrated with full use of OTEC manufactured hydrogen and oxygen and followed by catalytic synthesis of methanol will be evaluated. A design study of this possibility based on established technologies for coal gasification and methanol synthesis has been completed. Favorable results led to a second iteration which would employ a recently developed gasifier of higher efficiency than the commercially available design. This study is underway.

III. University of California, Marine Sciences Group - FY83 Funding: $200,000

Seacoast Test Facility (STF) Environmental Compliance

This project is to prepare a plan for environmental compliance, secure permits and develop compliance documents which satisfy Federal, State, and local regulations for the STF.

An Environmental Review Plan has been prepared and accepted, in principle, by NEPA Affairs Division. The plan served as the basis for the OTEC-1 CWP deployment approval. Preparation of the Notice of Intent is underway. Initial efforts on the preparation of the Environmental Impact Statement are underway, including liaison with the State of Hawaii.

OTEC Plant Flowfield

This project is to assess OTEC-induced modifications to the ocean and shore area as a result of the large water volumes required by OTEC operations.

Existing computer models have been acquired and checked out on the UCB IBM CMS 3370 system. Initial test runs are under development and will be used to assess the suitability of the models for OTEC conditions. These initial tests will be followed by physical model verification studies.

OTEC Bottom Assessment

This project is to provide an evaluation of marine geological/geophysical/geotechnical methods critical to OTEC bottom assessment to provide an integrated bottom assessment strategy.

The effort is to include testing of various combinations and sequences of methods for the evaluation of marine geologic situations likely to be found at potential OTEC sites.

Equipment and methods to be evaluated have been selected. Near-term

efforts will include completion of equipment checks on land, the selection of navigational benchmarks, and the completion of test schedules.

IV. Solar Energy Research Institute - FY83 Funding: $1,450,000

Heat and Mass Transfer Research

This project is designed to achieve significant improvements in the performance and effectiveness of alternative (i.e. open-cycle) OTEC systems through the development and evaluation of advanced components and subsystems. Pursuant to this objective, the project is to quantify the performance of advanced heat exchanger concepts, with emphasis on practical considerations of net power producing systems designs. This will include providing a data base through experiments and analytical comparisons of heat exchangers operated under prototypical scale and OTEC boundary conditions so acccurate predictions of system performance can be provided.

A draft report has been completed for the open-cycle performance analysis based on state-of-the-art component predictions and experimental data. Heat and mass transfer experiments have been started.

Project plans include parametric evaluations of design options for open-cycle OTEC using advanced data bases, hybrid condenser evaluations for open-cycle OTEC modeling of DC condensers with newly acquired data bases, and comparisons of fresh-water and sea-water evaporation.

Open Cycle (OC) OTEC Experiments and Facility Design at the Seacoast Test Facility (STF)

This project is to quantify the performance of advanced power system components and subsystems by designing and testing the more promising prototypes in sea water. This will provide an experimental data base which can support the definitive assessment of open-cycle systems and components using sea water.

This project has identified major issues, coordinated equipment resources, identified dissolved gas measurement instrumentation, and conducted shake-down and preliminary tests for the heat and mass-transfer experiments.

Near-term plans include investigation of turbine options for the STF and development of a conceptual design review package for the STF OC-OTEC power system experiment (including performance evaluations and cost projections).

V. National Oceanic and Atmospheric Administration - FY83 Funding: $1,100,000

At-Sea Test Program

This project is to design, fabricate, and deploy (at sea) a suspended and slope-mounted 1/3-scale fiberglass reinforced plastic model cold-water pipe, thus demonstrating FRP technology for large scale CWPs.

Design, fabrication, and at-sea CWP suspended deployment have been completed. The slope-mounted experiment is underway.

The CWP will have two 85-ft sections cut from either end to be used as test articles in Phase 3, Down-Slope Test. The two sections will be joined as planned, and placed on the foundations.

Shelf-Mounted Scale Model Test

This project is to carry out a model test program to assist in optimizing the structure for the 40MWe shelf-mounted platform concept. Test data, photographic documentation, and models are to be provided by the contractor. The contract award for model construction and testing has been made.

Fiberglass Reinforced Plastic (FRP) Cold Water Pipe (CWP) Material Tests

This project is to conduct long-term fatigue tests of FRP material specimens in sea water.

Tests have been conducted and interim results have been published.

Appendix B

Description of the Natural Energy Laboratory of Hawaii

and the

Seacoast Test Facility

(Prepared by the Laboratory Director)

T. H. Daniel - November 1983

HISTORY AND PRESENT STATUS OF THE NATURAL ENERGY LABORATORY OF HAWAII AND THE SEACOAST TEST FACILITY

In 1974, the Hawaii State Legislature set aside 328 acres of state-owned land at Keahole Point in the Kona District of the Big Island of Hawaii for research into renewable energy resources. The site was chosen because of the easy access to deep cold water provided by the steep offshore slope, the nearness of air and sea transportation facilities, and the availability of the land.

The initial legislation established a Board of Directors including State, County, and University of Hawaii officials to oversee the development of the facility. The Laboratory is funded through the State Department of Planning and Economic Development, independent of the University of Hawaii.

The State purpose in founding the Laboratory was to promote and encourage research into alternate energy sources by providing a facility where appropriate investigations could be pursued by various organizations from both the private and public sectors. It was envisioned that the laboratory would be self-supported by user fees. The State itself did not propose to perform the research. The Board of Directors of NELH is charged with selection of projects which are directed toward the goals of alternate energy development.

Initial development of NELH between 1974 and 1978 involved a series of environmental baseline studies and surveys leading to the establishment of permits for performing research at Keahole Point. Some Federally funded projects on OTEC biofouling and corrosion were conducted in the offshore research corridor, though these were limited by the ruggedness of the jeep road which provided access to the site. Mini-OTEC was positioned in the NELH research corridor.

In 1978, the Research Corporation of the University of Hawaii (RCUH), acting on behalf of the NELH Board of Directors, proposed to the Federal Department of Energy (DOE) the development of a Seacoast Test Facility (STF) at NELH. A detailed design was prepared to meet DOE specifications for a shore-based research laboratory intended to complement the floating experiments planned for the OTEC-1 vessel.

The initial agreement between RCUH and DOE called for the State to provide the access road, utilities and site preparations worth about $5 million. The DOE was to provide the remainder of the estimated $16 million required laboratory construction.

Road construction and site preparation were begun in the Fall of 1979 while Mini-OTEC was successfully demonstrating net energy production just offshore. Major reductions in DOE funding caused largely by cost overruns on OTEC-1, forced a significant reduction in the size and capabilities of the planned laboratory facilities. However, a laboratory building was completed in early 1980 followed by an administration building and power center later the same year.

Available funding was insufficient for installation of the planned 82 cm (32") warm and cold water pipelines, but an interim 30 cm (12") warm seawater system was designed and installed in early 1981. Biofouling and corrosion measurements were initiated in July of that year and have continued to the present time. Installation in August 1982 with State funds of an extended sea water intake has greatly improved the purity of the warm water supply. The water appears to be representative of open-ocean tropical surface seawater, and is thus ideal for OTEC baseline research.

The State of Hawaii, recognizing the importance of research into potential cold seawater aquaculture byproducts of OTEC, expended State funds for the installation of a unique 12" interim cold seawater supply. The 1.6 km (mile)-long pipeline, which brings cold deep water from 585 meters (1925 ft) depth into the laboratory was installed in December 1981. Pumping of the deep water began in March 1982. After some initial pump failures, continuous cold seawater flow has been maintained since August of 1982 (except for a brief period following hurricane Iwa in November 1982).

Experiments using the cold water supply have demonstrated the possibility of culturing salmon, rainbow trout, Maine lobster, abalone, kelp and nori (a Japanese seaweed delicacy) in the outfall from an OTEC plant. Several of these products appear to have economic potential at least equal to that of the energy which would be produced. Funding for these experiments has come from private companies, from State of Hawaii development funds, and from the National Sea Grant program.

Though installed primarily for aquaculture research, the cold seawater supply has also been used for some of the DOE-supported biofouling and corrosion experiments on candidate OTEC heat exchanger materials and configurations. Additional experiments have recently begun, funded by DOE through the Solar Energy Research Institute (SERI), using the warm and cold seawater supplies to investigate heat and mass-transfer in both the Claude and the mist-lift open cycle OTEC systems.

Experimentation in all of these areas continues at NELH. A core-staff of 91 technical personnel hired by RCUH operates the facility and the DOE experiment program for the NELH Board. This core staff is augmented by a variable number of investigators and technicians working on the various projects.

Though the initial goal of a laboratory self-supported by user fees remains elusive, project support represents a growing proportion of NELH income. Of the approximately $550,000 FY 1983 operating budget, $200,000 comes from the Hawaii State Legislature, $300,000 comes from DOE for operating the biofouling and corrosion experiments, and the remaining $50,000 comes from the various private companies and State and Federal agencies supporting projects at the laboratory. This represents a significant improvement over previous years when fluctuations in Federal funding necessitated much larger State contributions.

Future plans for NELH include the installation of a larger, more permanent seawater supply system for both warm and cold water. The recent (October 1983) failure of an attempt by the State to deploy the OTEC-1 1.3 m (48") cold water pipe off Keahole Point may slow development plans somewhat,

but work is actively proceeding to make the most of the situation and to determine what size and type of pipe will best meet the projected future needs of the laboratory. Planned projects include a 1-acre 30 kW solar pond OTEC demonstration and medium-sized open- and closed-cycle net-power-producing OTEC plants designed to provide data for commercial technology development.

To supplement a small ongoing corrosion research project funded by Alcoa, both Alcan, International and Lockheed Advanced Marine Systems have indicated strong interest in initiating OTEC-related research projects. NELH welcomes proposals from both public and private entities desiring to utilize its unique research facilities.

T. H. Daniel - November 1983

SUMMARY OF RESEARCH RESULTS FROM NELH/STF - 1981-1983

Closed-Cycle OTEC Heat Exchanger Research

- Biofouling rapidly reduces the efficiency of evaporator heat exchangers, rendering them unsuitable for OTEC after 15-20 days of warm water flow.

- The biofouling in Hawaiian waters can be totally controlled by extremely low levels of chlorine (70 ppb) applied for only one hour per day. No change in heat transfer has occurred for aluminum, titanium or stainless steel after nearly 2½ years of continuous water flow using this chlorination schedule.

- No biofouling occurs when the deep cold water flows through candidate heat exchanger materials. There has been no change in heat transfer after 15 months of operation, even including eleven days when the water sat in the tubes during pump breakdowns following Hurricane Iwa.

- No pitting corrosion appears in tubes of various aluminum alloys exposed to flowing surface seawater. Lifetimes in excess of 30 years for aluminum evaporators can be predicted by extrapolating these data.

- Some pitting corrosion does occur in aluminum alloys exposed to the cold deep water. Unless this can be controlled, it might preclude the use of these alloys in OTEC condensers.

Cold Water OTEC Aquaculture Research

- Rainbow trout grow well (as "steelheads") when transferred from freshwater to cold deep seawater after smoltification. In excess of 300 pounds of fish can be grown in a 600 gallon tank through which cold deep seawater flows.

- Nori (Porphyra tenera), an edible seaweed considered a delicacy in Japan, grows extremely well in a tumble-culture using the deep cold seawater and vigorous aeration. Growth rates of about 35% increase in weight per day were obtained over the first 15 days, and 20 to 40% of the dissolved nitrogen and phosphorus available in high concentrations in the deep water were extracted by the seaweed in one pass through the system.

- Abalone do very well in the cold deep water because of:

1) the very low pathogen levels in the deep water supply,

2) the high dissolved silica content which permits rapid growth of the diatoms which feed the larval abalone, and

3) the high protein content of kelp (Macrocystis) raised in this water, which improves the growth of the adult abalone which feed on the kelp.

- Maine Lobster can be grown in the water mixed with appropriate amounts of surface seawater. The capital-intensive nature of the apparatus needed for this culture appears to make it uneconomical at present.

Open-Cycle OTEC Research

- Preliminary heat and mass transfer measurements indicate seawater efficiencies for spout evaporators and condensers similar to those obtained earlier with fresh water.

- The thermodynamic efficiency of the mist-lift process appears to be as predicted for the experimental apparatus. The mist generator can be operated for at least several hours without the seawater clogging its small holes.

- Experiments are just beginning to analyze the composition of dissolved gases in the warm and cold seawater before and after open cycle processes.